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ABSTRACT

To improve speech patterns of deaf children, a visual aid was developed which assists in the training of velar control. A small accelerometer is attached to the nose, and its output presented on a computer-controlled visual display. The display then may be used as a training aid, or for analyzing recorded or live speech. Properties of accelerometer output in speech of people with normal hearing and children with severely impaired hearing are compared. The data show inadequate velar control, particularly improper nasalization of certain vowels for a significant number of deaf children. Some comments are made on the development of procedures for the training of velar control using the display as an aid. (SK)

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ASSESSMENT OF NASALITY IN THE SPEECH OF DEAF CHILDREN

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Table of Contents

Abstract

Nasality is widely recognized as a problem in the speech of many deaf people. This paper describes one approach to the assessment of that problem and to the development of visual aids to assist in the training of velar control. The approach involves detection of the velar opening during sounds by means of a small accelerometer attached to the nose, and presentation of the accelerometer output on a computer-controlled visual display. The display may be used as a training aid, or for the purpose of analyzing either recorded or live speech. Objective data are presented on some of the properties of the accelerometer output for the speech of people with normal hearing and of a number of children whose hearing is severely impaired. These data show inadequate velar control, particularly improper nasalization of certain vowels, for a significant number of the deaf children. For a group of the hearing-impaired children, subjective judgments of the adequacy of velar control and of other speech attributes were obtained. Correlations among these judgments and relations between nasality judgments and the objective measures are shown. Some comments are made on the development of procedures for the training of velar control using the display as an aid.

Assessment of Nasality in the Speech of Deaf Children

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NASALITY AS A PROBLEM IN THE SPEECH OF THE DEAF

It has long been recognized that one source of difficulty with the speech of many deaf people is inappropriate control of the velum. When the velum remains low during a vowel sound that is normally nonnasal, the resulting acoustic coupling between mouth and nose cavities can modify the properties of the sound and can lead to a subjective impression of nasality. Failure to raise the velum during an obstruent consonant (a consonant produced with pressure build-up in the mouth) leads to a marked change in the properties of the sound during the interval of consonantal constriction, and in some cases causes a nasal consonant to be generated rather than an obstruent. On the other hand, if the velum is not lowered during a nasal consonant, pressure can build up in the mouth, and a stop rather than a nasal consonant is heard.

Inadequate or improper control of the velum has usually been considered to be the primary cause of the subjective impression of nasality (Hudgins, 1934), although some investigators have

suggested that the perception of nasality can also be influenced by other factors such as malarticulation, pitch variations, and speech tempo (Colton and Cooker, 1968). The term hypernasality is sometimes used to describe the condition where the passage to the nasal pharynx is left open when it should be closed; hyponasality results if the passage is closed when it should be open. Many deaf speakers who have problems with velar control exhibit both hyponasality (by producing some nasal consonants with a closed velum) and hypernasality (by producing some vowels and nonnasal consonants with a lowered velum).

In spite of the fact that the problem of nasality has been widely acknowledged for many years--Brehm (1922) referred to it as "the nightmare of all speech teachers"--it remains a difficult one to diagnose and remedy for two reasons. First, nasality is apparently a difficult quality to judge by ear. The difficulty is due in part perhaps to the fact that distinctive perceptual features of nasality are not clearly defined, and in part to the fact that the overall quality of speech is affected by many factors that may interact with nasality in complex ways. Subjective judgments of hypernasality in a deaf child's speech are complicated by the fact that the expression "nasal speech" may include more than one type of deviation from normality. For example, a deliberate constriction of the nasal pathways modifies the resonant characteristics of nasal consonants and adjacent vowels to produce a type of "nasal speech" which does not necessarily involve improper velar control.

A second reason for difficulty in the diagnosis and remediation of nasality is that the articulatory gesture involved in closing and opening the passage to the nasal cavity (raising and lowering the velum) is not visible, and such proprioceptive cues as exist do not seem to be cognitively meaningful. The deaf child who must use lipreading as his primary speech input does not receive information on the state of the velum. Hypernasal vowels are visually indistinguishable from nonnasal vowels, just as the plosives /b/, /d/, and /g/ are visually indistinguishable from the nasal consonants /m/, /n/, and /ŋ/. Even the deaf child with usable residual hearing typically cannot discriminate auditorily between nasalized and nonnasalized vowels. This problem is further complicated by the fact that in the environment of a school for the deaf, or even among family and friends, the deaf child's own speech is understood partly on the basis of its visual features rather than its auditory ones. Thus, the absence of appropriate velar control may not prevent the child from being understood, and a powerful motivator for acquisition of this skill is missing.

Both of these factors--the difficulty of detecting nasality auditorily and the lack of natural nonauditory cues to aid the child in learning to make appropriate use of the velum--demonstrate the need for the development of reliable, practical, and objective methods for measuring and representing the nasality of speech.

The purpose of this paper is to describe one approach to this problem. First, we describe a method of detecting and displaying nasality information; second, we present some nasality data that have been obtained from both deaf and hearing speakers. The procedure for detecting and displaying nasality information is currently being used in an experimental system of speech-training aids for the deaf (Nickerson and Stevens, 1973). Training procedures that utilize the displays are still being evolved.

The method for detecting nasality is not, of course, restricted to the speech of the deaf. Of particular interest is the potential application of the method to the evaluation of nasality in the speech of individuals with cleft palate.

DETECTION AND DISPLAY OF NASALITY

Nasality is difficult to detect from direct measurements on the speech signal. Several acoustic correlates of nasality in vowels for adult speakers have been investigated, among them shifted and "split" first formant (Fujimura, 1960; House and Stevens, 1956), and enhanced amplitude of the lowest harmonics (Delattre, 1955). These acoustic attributes are rather subtle, however, and the particular way in which nasality is manifested in the acoustic signal varies from vowel to vowel.

Several methods of measuring nasality by other means have been proposed. These methods detect the flow of air through the nose (Lubker and Moll, 1965; Quigley, et al., 1964), they measure the acoustic energy radiated from the nostrils (Fletcher, 1970;

Shelton, et al., 1967), or they pick up the vibration on the surface of the nose (Holbrook and Crawford, 1970). The procedure employed in this study uses the last of these methods. The vibration is transduced by means of a small accelerometer attached to the surface of the nose (Stevens, Kalikow, and Willemain, 1974). The accelerometer weighs just 1.8 gms, and, as Figure 1 shows, is very small. It has a negligible distracting influence on the speaker, and presumably does not affect her speech.

When the velum is lowered during a voiced sound, the increased sound energy in the nasal passages causes vibration of the nose and an increased output of the accelerometer. This output is rectified, low-pass-filtered (averaging time of about 20 msec.), sampled (at 10-msec. intervals), log-converted, and displayed on an oscilloscope as a time function.

An example of this time function for a phrase produced by a normal male speaker is shown in Figure 2. The phrase is "You can drink your milk." The nasal output for the first (nonnasal) vowel is about 20 dB below the peaks that occur during the nasal consonants. Vowels preceding nasal consonants (/æ/ in <u>can</u> and /ɪ/ in <u>drink</u>) are nasalized, as expected, and nasalization even extends across word boundaries, as in the word <u>your</u>, which precedes the /m/ in <u>milk</u> without an intervening obstruent consonant.[1]

Fig. 1. Accelerometer attached to nose of subject. Also shown is a small microphone used for transducing the acoustic signal. The accelerometer-microphone arrangement provides input signals to a system of speech-training aids.

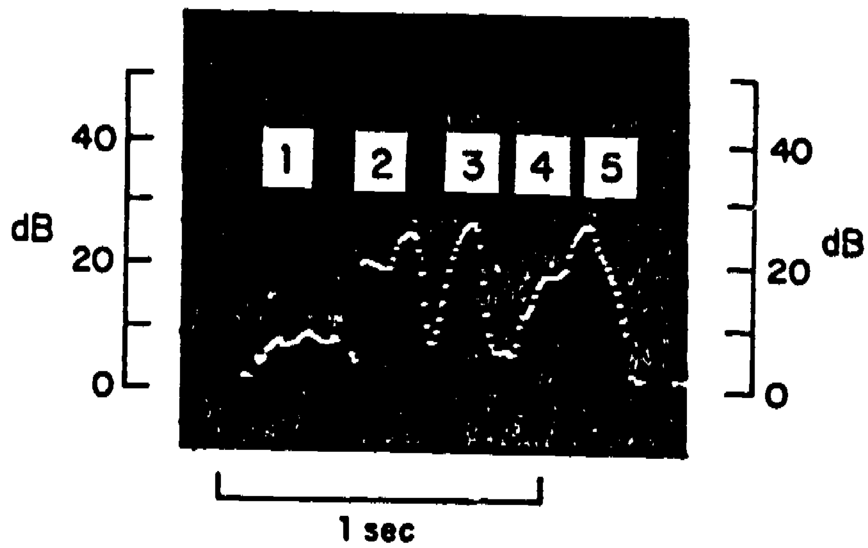

Fig. 2. Display of amplitude of output of nose accelerometer as a function of time for the sentence, "You can drink your milk," produced by a normal adult male speaker. The five syllables in the sentence are identified above the display. See text.

NASALITY MEASUREMENTS FOR NORMAL SPEAKERS

Vowels

As Figure 2 shows, the nasal accelerometer gives some output during nonnasal vowels, although this output is well below that for nasal consonants and nasalized vowels. In order to obtain data on the degree to which the accelerometer output can be used to discriminate nasal from nonnasal sounds, a number of measurements of the accelerometer signal have been made for normal-hearing children (n = 17, ages 8-15) and adults (11 male, 13 female) producing monosyllabic words containing no nasal consonants and words with nasal consonants. The nonnasal words were selected to include a range of nondiphthongized vowels, while the nasal words included nasal consonants in both initial and final position. The list of words[2] for which measurements were obtained is given in Table 1.

Measurements of the peak output of the accelerometer were made, using the computer display in conjunction with a procedure that permitted the observer to adjust a cursor and to obtain a numerical value of the output directly from the display. Examples of the display used in making these measurements for a nasal word and for a nonnasal word are shown in Figure 3. In each case, the cursor is adjusted to a point where a peak occurs in the accelerometer output. For a nonnasal word, the peak occurs during the vowel, whereas for a nasal word the peak is in the nasal consonant. The

Table 1. List of words recorded by normal-hearing subjects and by deaf children.

Nonnasal Words	Vowel	Nasal Words
leaf	i	mouth
dish	ɪ	nail
dress	ɛ	arm
flag	æ	spoon
socks	ɑ	queen
glove	ʌ	clown
straw	ɔ	ring
church	ɝ	snow
book	ʊ	jump
shoe	u	hand
		think

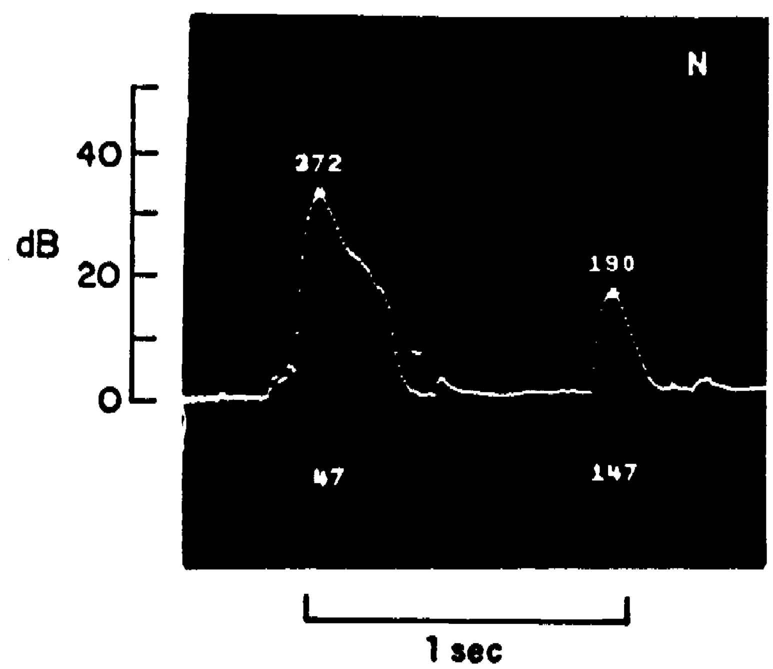

Fig. 3. Nasality display for the words "mouth" (left) and "socks" (right). Peak recordings of accelerometer output (in units of 0.1 dB) are shown above each contour. The numbers below the curves indicate the locations of time samples (in units of 10 msec.) where readings were obtained.

numerical amplitude values indicated on the display at the position of the cursor are in units of about 1/10 dB. For purposes of discussion, we shall use the term "peak nasality" to indicate the peak value of the accelerometer output obtained by this procedure.

The peak nasality for the words with nasal consonants showed some variability from one utterance to another, presumably caused by fluctuations in voice level of the speaker and by differences in the place of articulation of the nasal consonant and the position of the consonant in the word. The standard deviation in these readings for nasal consonants for a given speaker was 1-3 dB, depending on the speaker. On the average, the peak nasality for the nasal consonant /m/ was 1-2 dB below the value for /n/ and /ŋ/. The peak nasality for final nasal clusters was 1-2 dB below that for initial or final singleton nasals. An average reading of peak nasality over all nasal words in Table 1 was calculated for each speaker.

The peak nasality in the vowels for nonnasal words depended to some extent on the vowel. For each speaker, the difference between the average over nasal words and the peak nasality for each nonnasal word was calculated. (In the example in Figure 3, the difference in peak nasality for the nasal consonant and the non-nasal vowel is 182 units, or about 18 dB.) These differences, averaged over the 17 children are shown for each vowel in Figure 4.

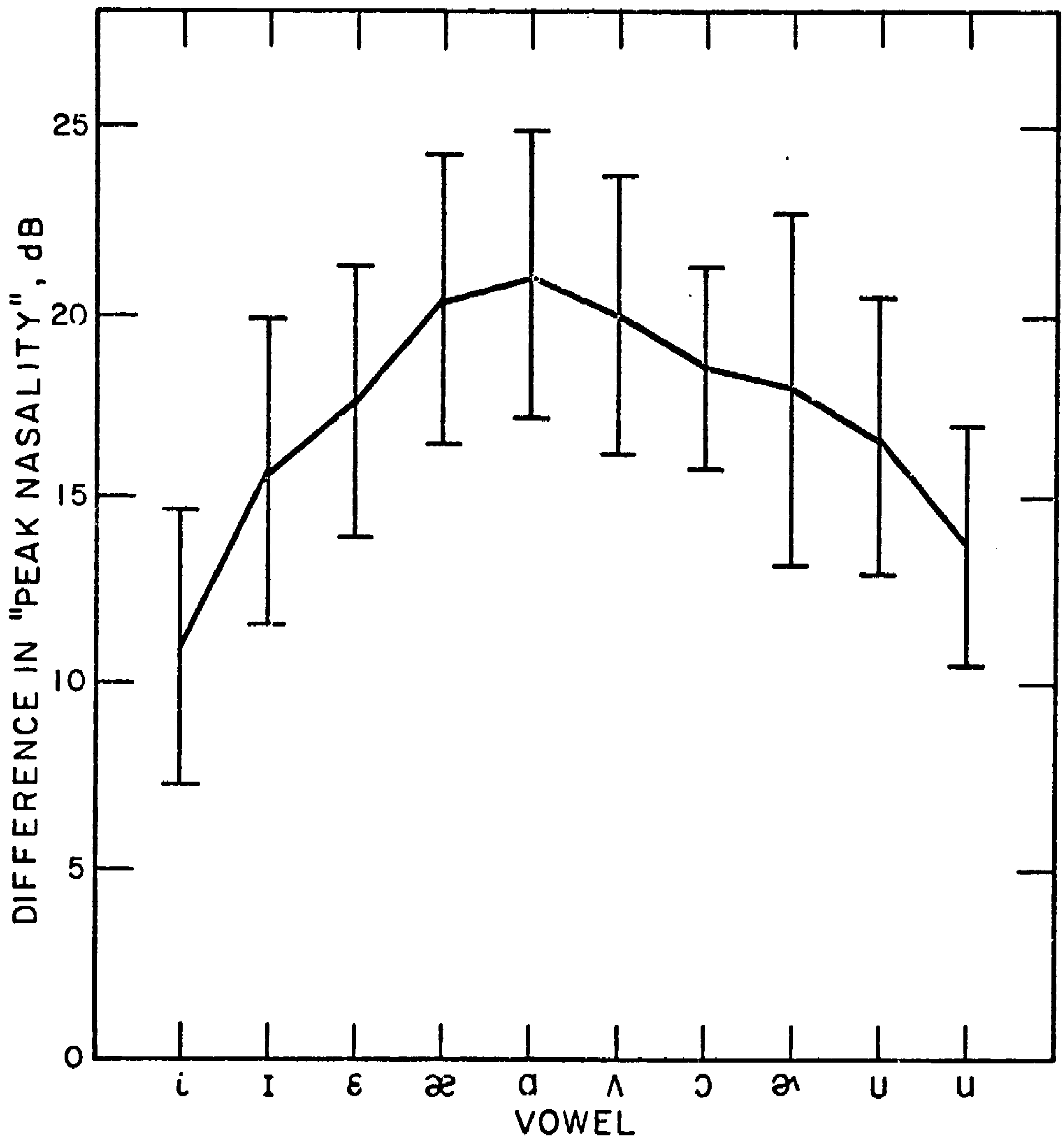

Fig. 4. Average difference between peak nasality for (1) monosyllabic words containing nasal consonants, and (2) nonnasal monosyllabic words. The vowels forming the syllabic nuclei for the nonnasal words are shown on the abscissa. Averages for 17 normal-hearing children. Vertical bars indicate standard deviations across speakers.

The vowel /i/ clearly shows the least difference in nasality reading compared with nasal words--a difference of about 11 dB, on the average. The other high vowel /u/ has a difference of about 14 dB. For non-high vowels, the difference is greater, and is about 20 dB, on the average. As shown by the vertical bars around each point, which indicates standard deviations across speakers, there are considerable differences in the nasality readings from one individual to another. These are presumably due to fluctuations in voice level, anatomical differences, and speaking habits.

Data for adult males, adult females and children are compared in Figure 5. The curves show the same general trends as the data in Figure 4. Differences between men, women and children are not large, although there is a tendency for the data for children to be slightly above those for men and women, at least for some vowels. This difference can presumably be ascribed to the higher average fundamental frequency and formant frequencies for children. The standard deviations for adult speakers are roughly the same as those for children.

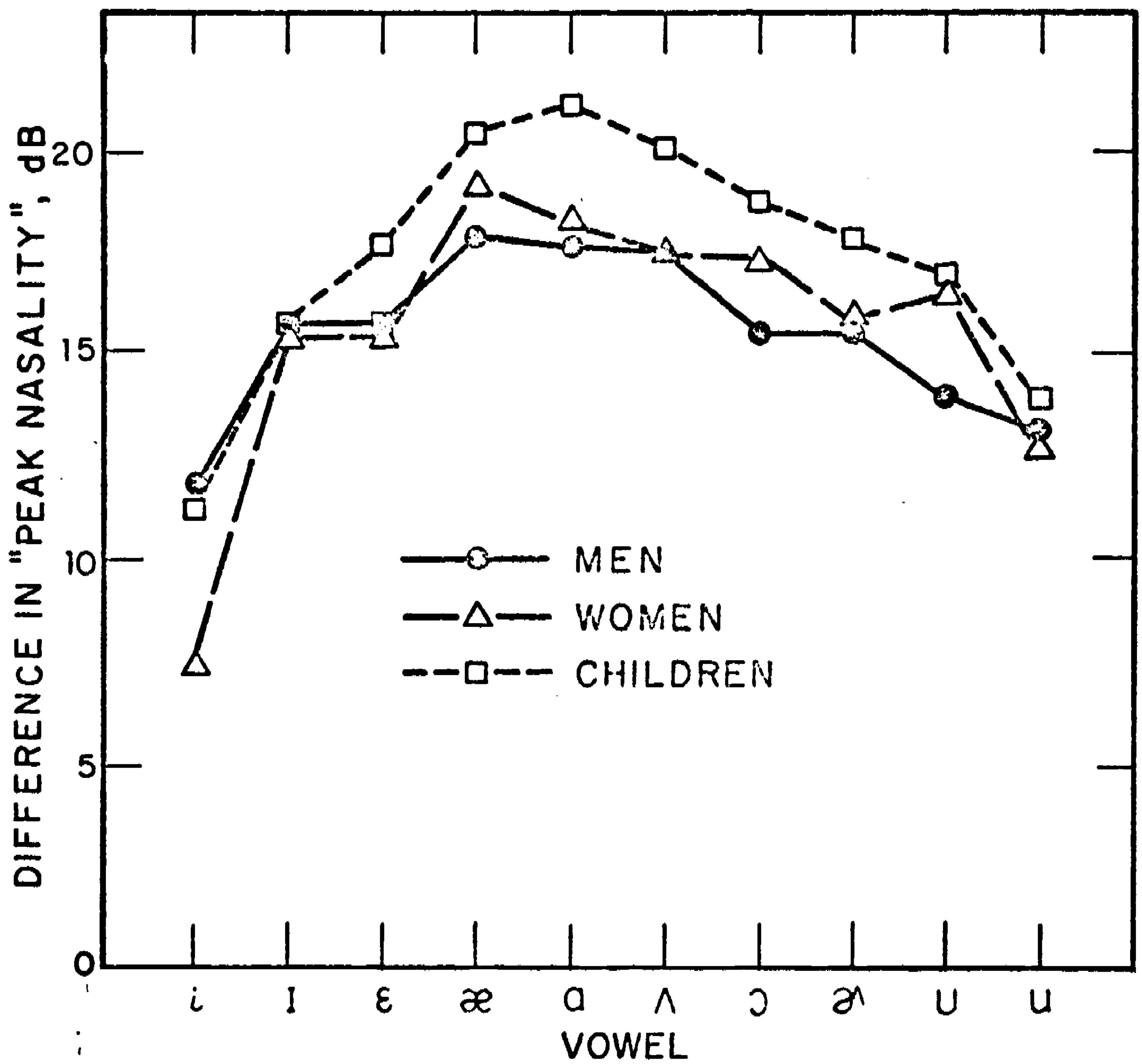

Fig. 5. Same as Fig. 4, except average data are compared for three normal-hearing groups: adult males (11 speakers), adult females (13 speakers), and children (17 speakers).

The differences in nasality readings from one vowel to another, shown in Figures 4 and 5, could have been the result of the influence of the initial or final consonant rather than being an inherent property of the vowel, since different consonants occurred in the words with different vowel nuclei. In order to examine this possibility, a set of monosyllabic nasal words and words containing different vowels in context hVd was recorded for a subset of the adults and children used to collect the data in Figure 5. The nasal accelerometer output was processed in the same way as indicated above, to obtain difference readings for the nonnasal vowels relative to the nasal consonants. The data for the vowels in the hVd context were almost identical to those for the words in Table 1 with the random consonantal contexts, indicating that the results of Figures 4 and 5 represent inherent properties of the individual vowel nuclei, and are not greatly influenced by consonantal context.

The signal that reaches the accelerometer is probably the result of excitation of the tissue of the nose by sound energy in the nasal cavity (although the possibility that some of the energy is structure-borne through the maxilla cannot be ruled out). Sound energy reaches the nasal cavity either by passing through a partially open velopharyngeal port, or through the palatal structure if there is no velar opening. In either case, one would expect the acceleration amplitude on the nose surface to be greater at low frequencies than at high frequencies. Thus, it is not

unexpected that the peak nasality reading is greater for vowels with low first-formant frequencies[3] (i.e., /i/ and /u/).

The data in Figures 4 and 5 provide some indication of the differences between nasality readings for nasal and nonnasal sounds in monosyllabic words generated by normal speakers. If a display of the amplitude of the accelerometer output is used in a speech-training situation with deaf children, these data can serve as a guide for specifying the nasality readings that should be achieved for different vowels. The procedure would be to obtain first a baseline nasality reading for a nasal consonant, and then require that the reading for a given nonnasal vowel be less than this baseline reading by the amounts suggested by Figures 4 and 5 (assuming the speech level does not change appreciably, as discussed in Footnote 1).

Nasal Consonants in Context

Ability to produce steady vowels (or vowels in nonnasal CVC words) within proper limits of nasality does not, of course, guarantee that an individual can exercise proper velar control in more complicated phonetic environments. When an utterance of several syllables contains one or more nasal consonants, there is a requirement that the velum be raised and lowered in proper synchrony with the movements of other articulatory structures. When a nasal consonant is preceded and followed by vowels or by sonorant consonants (consonants produced with no pressure build-up in the mouth), the velum can remain open for some tens of milliseconds before and after the nasal consonant.

That is, the movements of the velum can be rather sluggish. The presence of an obstruent consonant, however, requires that the velum be closed, since pressure must be built up in the mouth.

The spread of nasality into vowels adjacent to a nasal consonant is illustrated in Figure 6. The sentence "We were in Europe" contains one nasal consonant with several non-obstruent sounds preceding and following the consonant. As the nasality display demonstrates, there is a broad peak in the accelerometer output, extending over about 260 msec. (indicated by the positions of the two cursors). Also shown in the figure is a display of the "amplitude" of the speech signal,[4] and a spectrogram of the utterance, on which the cursor positions are marked. The region of tongue constriction for the nasal consonant (of duration about 90 msec.) can be easily observed (arrows above the spectrogram). Evidence of nasality in the vowels adjacent to the consonant can be seen in the spectrogram, particularly (in the preceding vowel) the split first formant that is characteristic of nasalized vowels. The peak in nasality occurs at a dip in the amplitude of the speech signal between two syllabic nuclei, as would be expected. In contrast to the nasality display in Figure 6 is the contour for the sentence "We were in Greece," shown in Figure 7. In this case, there is an abrupt drop in nasality following the /n/, since the velum must be closed to permit pressure build-up for the /g/. (The drop in nasality shown in the figure is slower than the actual drop, since there is some smoothing in the nasality display.)

Report No.
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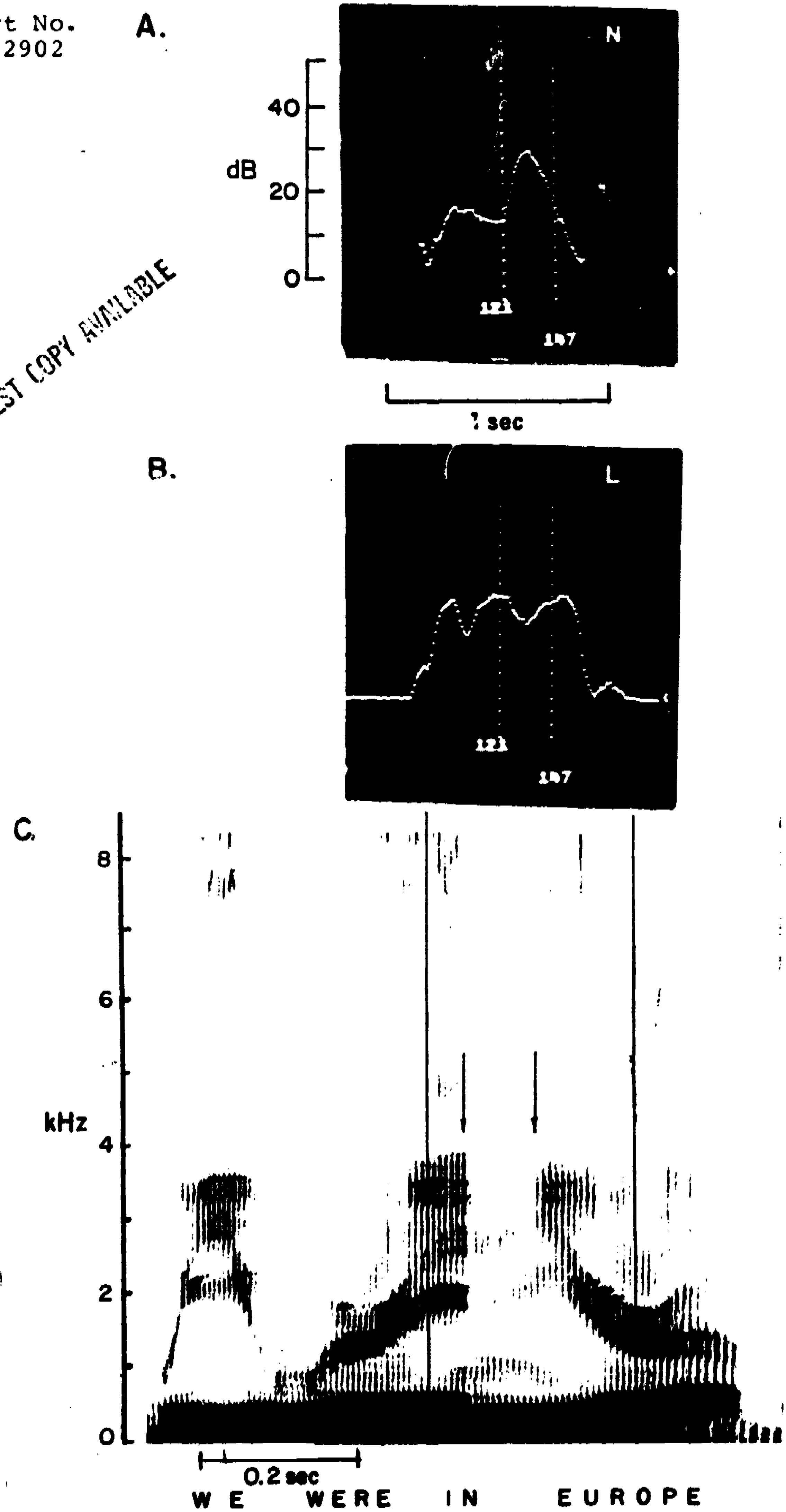

Fig. 6. Displays of (a) output of nasal accelerometer, (b) "amplitude" of speech signal, and (c) spectrogram, for the utterance "We were in Europe." The two vertical cursors in (a) and (b) indicate estimates of the onset and offset of acoustic coupling to the nasal cavity. These times are also represented by vertical lines in the spectrogram. The arrows on the spectrogram show the beginning and end of tongue closure in the mouth for the consonant /n/.

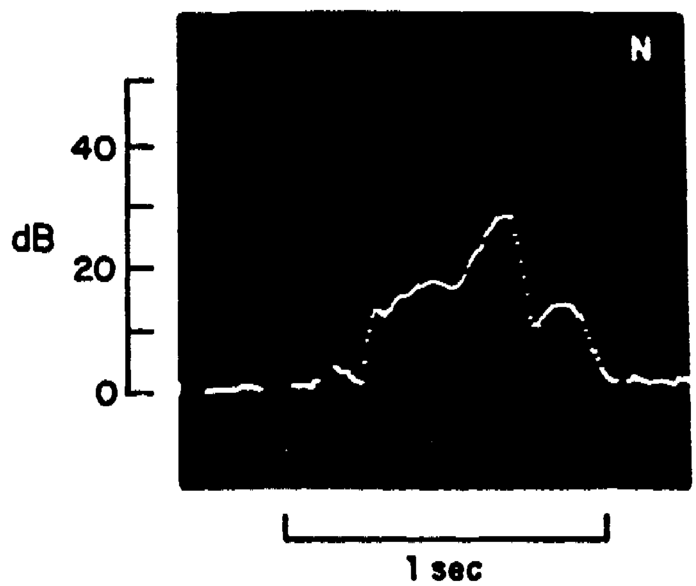

Fig. 7. Display of nasal accelerometer output for the sentence "We were in Greece."

Other examples illustrating the dynamics of velar control are shown in Figures 8 and 9. In Figure 3, the nasality and amplitude displays are given for the contras ing utterances "type out" and "time out." The nasalization in both vowels of the latter utterance (particularly the vowel preceding the nasal consonant) is apparent, whereas both vowels in the first utterance are nonnasal. Figure 9 shows the nasality display for the three words "cinder, sinner, sitter." There is an abrupt drop in nasality following the /n/ in the first word, with a nonnasal second syllable. Both syllables are nasalized in the second word, whereas both are nonnasal in the third word.

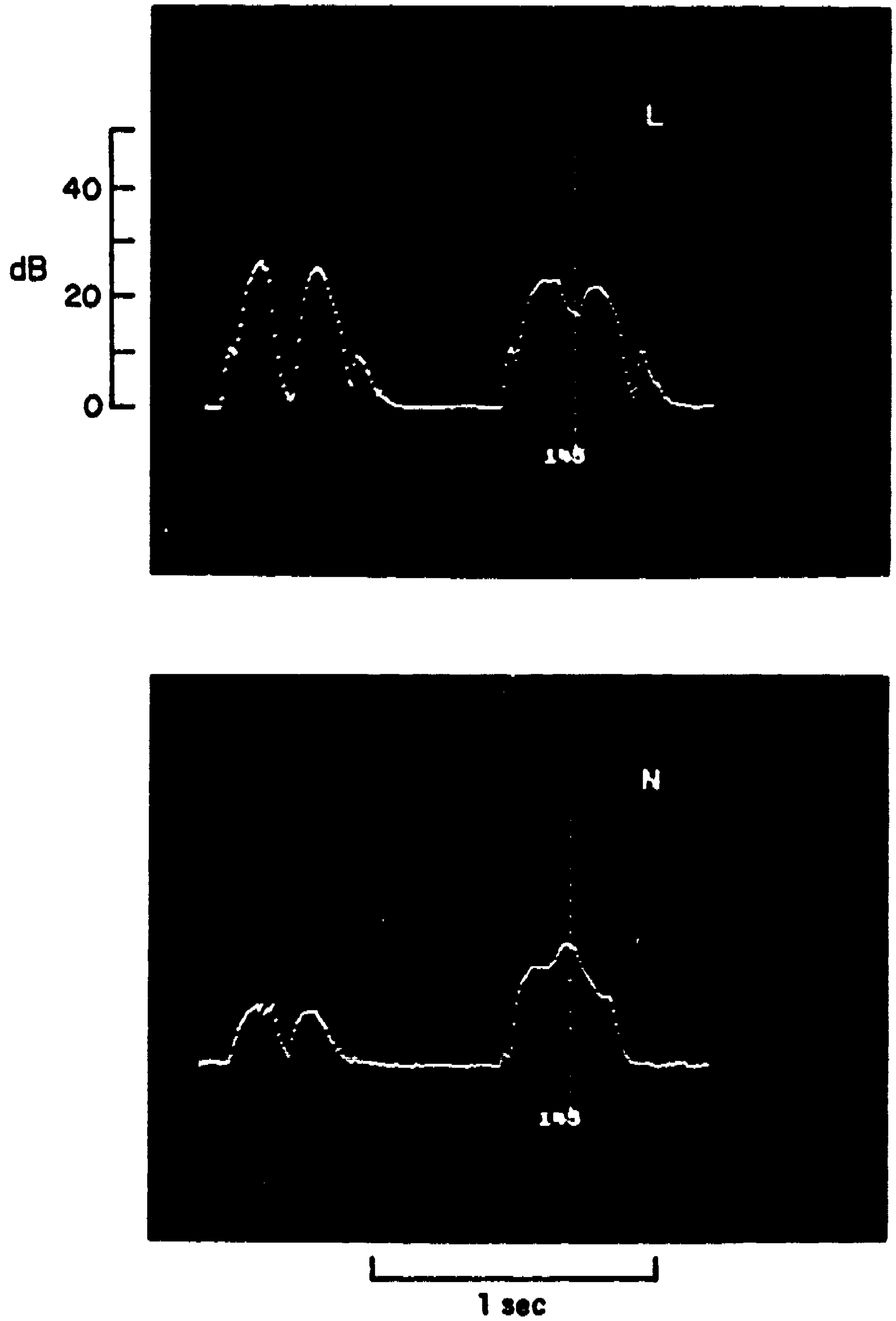

Fig. 8. Amplitude (top) and nasality displays for the utterances "type out" and "time out." The cursor is positioned at the nasality peak (coinciding with the amplitude minimum between vowels) in the second utterance.

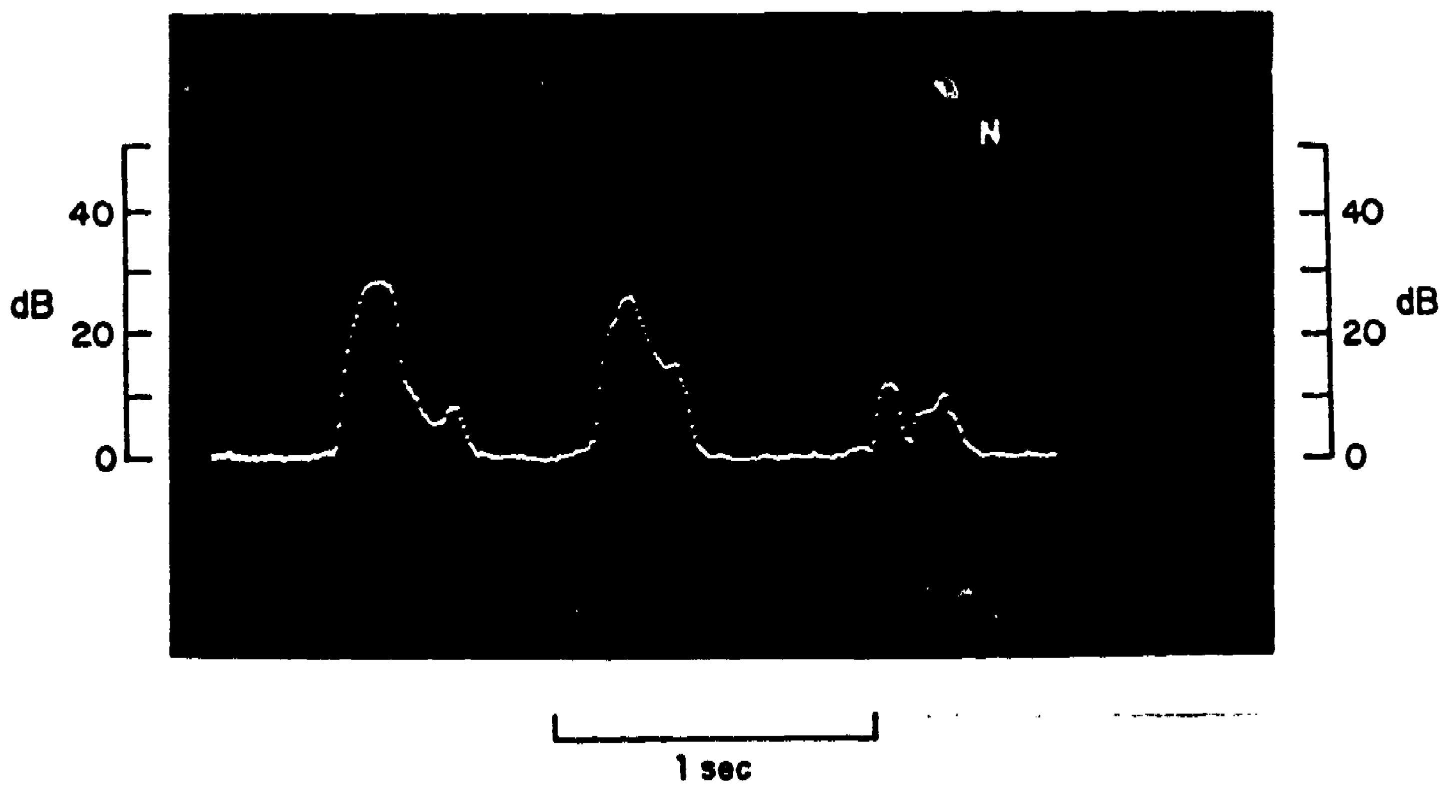

Fig. 9. Display of nasal accelerometer output for the three words, "cinder," "sinner," and "sitter."

NASALITY IN THE SPEECH OF DEAF SPEAKERS

Objective Measurements of Nasality of Deaf Children for Words in Isolation

As part of an effort to develop and test certain speech-training procedures that make use of a computer-based system of speech-training aids, recordings of speech were obtained from a number of deaf students. For one group of 25 students, recordings of the list of monosyllabic words shown in Table 1 were obtained in one session, and a series of objective measurements was made from the recordings, following procedures used in obtaining data for normal speakers, as discussed above. For each of the words in Table 1, the "peak nasality" was measured during the nasal consonant in the case of words containing nasal consonants, and during the vowel in the case of nonnasal words. There were, of course, many examples in which a stop consonant was substituted for a nasal consonant (i.e., hyponasality occurred), and the peak nasality during the consonant was significantly lower than it should have been. In a number of utterances with no nasal consonants, the nasality reading in the vowel was abnormally high. For all children, there were at least some nasal consonants in some words that were produced with a relatively large nasality reading, and which were judged by listeners to be adequate versions of nasal consonants. Average readings of peak nasality for these words were obtained for each of the deaf children. These averages provided reference nasality

readings; they correspond to the average readings over all nasal words that were obtained for normal speakers, as discussed above. Words containing nasal consonants that were not adequately nasalized were noted. The peak nasality was then measured for each of the nonnasal words, and these values were subtracted from the reference nasality readings for each speaker. Thus, for each word (and hence for each vowel, since the words were selected to contain one token of each vowel, as indicated in Table 1), a difference measure was obtained similar to the measures for normal speakers, shown in Figures 4 and 5.

The adequacy of velar control for the words containing nasal consonants was assessed for initial nasals, final nasals, and nasal clusters in final position. The data are summarized in Table 2. (The word snow was omitted from this summary. The nasal consonant in this word was, in fact, rarely denasalized.) Not unexpectedly, the children had the greatest problem in properly nasalizing the nasals in words with nasal-stop clusters. Generation of these words requires a velar opening-closing movement that is closely coordinated with the movements of the supraglottal articulators. About half of the children studied made a nasality error on at least one such word, and 12% made an error on all three of these words. Table 2 also shows that initial nasal consonants were produced with hyponasality more frequently than were final nasals.

Table 2. Percent of nasal consonants in each class which were denasalized or inadequately nasalized by deaf children.

	Percent Denasalized
initial nasals (nail, etc.)	16
final nasals (clown, etc.)	8
nasal clusters (jump, etc.)	36

Using the difference nasality measure noted above, each vowel in a nonnasal word was assessed for the adequacy of its nasal characteristics. The following criterion was used: If the difference measure for a vowel produced by a deaf child was more than one standard deviation below the curve shown in Figure 4 (i.e., below the lower end of the vertical bar), the vowel was considered to be improperly nasalized. The number of such hypernasal vowels was determined for each student, and the results are summarized in Figure 10 as a cumulative plot. The figure shows that 76% of the students examined had excessive nasality in at least half of the vowels in monosyllabic words. Thirty-six percent of the students had excessive nasality in at least eight out of the ten vowels studied.

The criterion for "excessive nasality" is, perhaps, rather severe, since some normal speakers would be judged to have nasal vowels by this criterion. The number of normals who do not meet this criterion is also shown in Figure 10, with adults and children being represented separately. The number of normals who would be judged to have excessive nasality (by the specified criterion) in more than two vowels is small.

The population of deaf students on which the data in Table 2 and Figure 6 are based was not necessarily selected to be representative of deaf students in general. The age range was 8 to 16 years, the numbers of girls and boys were about equal, all the children were from the Clarke School for the Deaf, and the

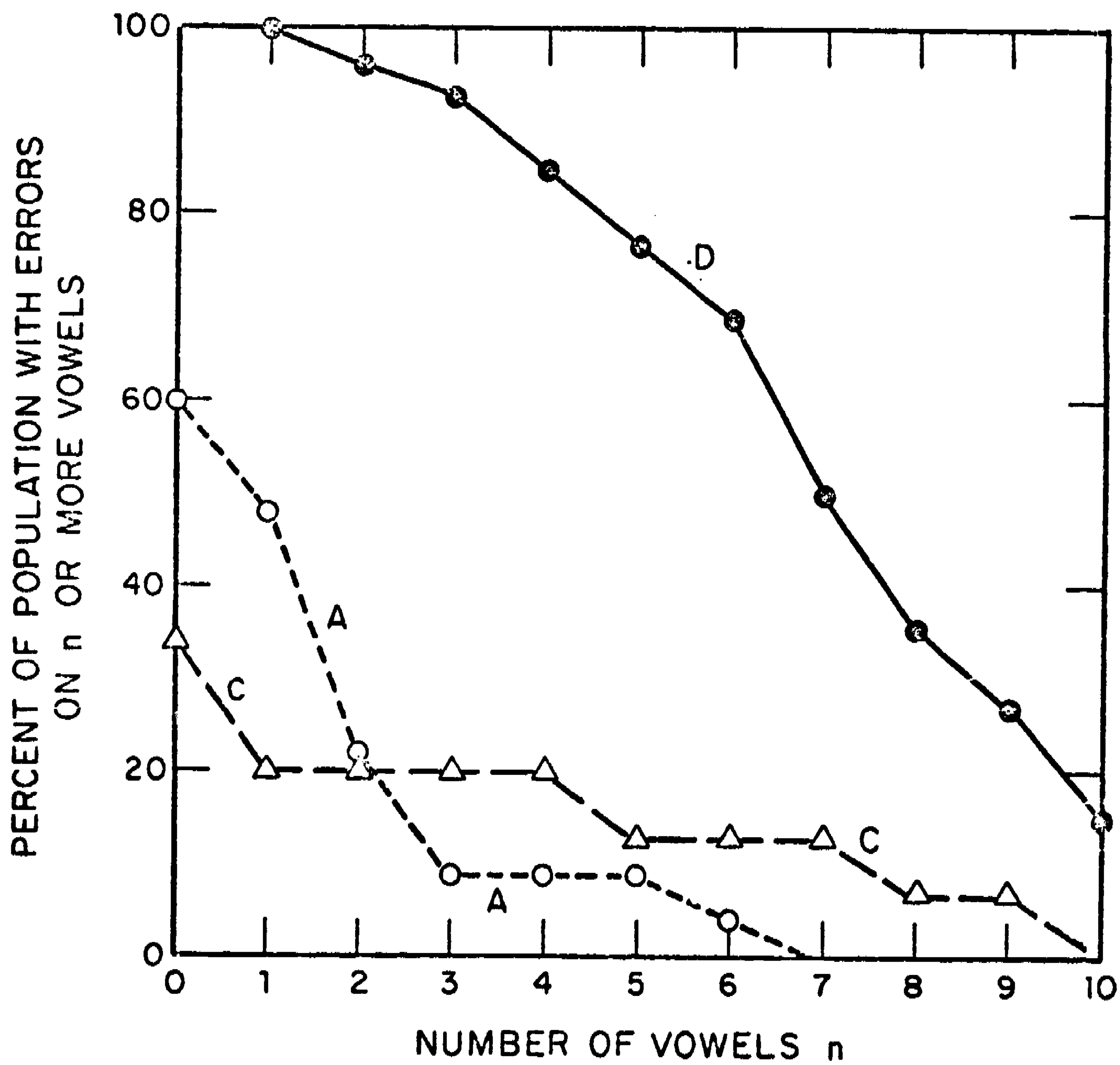

Fig. 10. Incidence of errors in nasality for nonnasal vowels produced in monosyllabic words by deaf children (D), hearing children (C), and hearing adults (A). Data based on objective measurements of nasality in ten different nondiphthongized vowels. Criterion for error in nasality is defined in text.

general speech intelligibility covered a broad range from 13 percent to 86 percent (based on number of words in sentences identified correctly by listeners). In view of the widely differing kinds of speech problems of deaf children and the variety of approaches to the speech training of such children, a sample of 25-odd students from one school could not be expected to be sufficient to represent the general population of deaf students.

More Extensive Data from Six Students

A more extensive set of speech material from six of the 25 students was recorded on two occasions--once before a series of experimental training procedures was begun, and once at the end of training. The recordings were analyzed by a set of objective procedures, and were also subjected to listener evaluations. In addition to the list of monosyllabic words recorded by the normal-hearing speakers (of which Table 1 forms a subset), the speech materials that were generated by this group included a list of 24 read phrases and sentences, and spontaneous speech produced in the description of picture sequences. Since these materials were recorded as part of a larger study, only some of the utterances were designed specifically to examine problems of velar control. The phrases and sentences that were studied particularly from the point of view of velar control are listed in Table 3. The first of these items has no nasals, the second and third have a number of nasal consonants with no intervening obstruent consonants, and items 4, 5, and 6 contain mixed stops and nasals.

Table 3. List of phrases and sentences that were examined for adequacy of velar control when produced by deaf children.

1. You lost your glove?
2. My money.
3. Many men are in Maine now.
4. You can drink your milk.
5. I went home Friday night.
6. A spoon and a dish.

The six students who recorded this more extensive material were selected for speech training because they had specific speech problems that required attention, and it was thought that the speech-training procedures that might be employed in the remediation of these problems could be assisted by using the computer-based system of displays. Five of the six students were diagnosed as having some problems with velar control.

Two types of listener evaluations were obtained from the material recorded by these six students. Four experienced listeners (teachers of the deaf) evaluated the recordings with respect to specific articulatory and suprasegmental aspects of the speech. Formal worksheets specified for each utterance the type of evaluation that was to be made. For example, the phrase "a spoon and a dish" was judged with respect to harshness, breathiness, average pitch, pitch range, intonation, rate of utterance, pause placement, and stress placement. Items 1-5 in Table 3 were judged with respect to adequacy of velar control. For each item the judgment was made on a five-point scale, the end points of which were defined as "no problem" and "serious problem." Words spoken in isolation were evaluated in terms of initial sound(s), vowel nucleus, and final sound(s), or a specified subset of these components. Similar judgments on individual speech sounds were made for some

of the words in the phrases and sentences. Listeners were permitted to listen to each utterance as many times as they wished before making their judgments. Table 4 lists the types of judgments that were made. Not all types of judgments were made on all utterances, although, in many cases, several types of judgments were made on a single utterance.

The same four experienced listeners plus eight "naive listeners" (listeners who had had little or no prior exposure to speech of the deaf) were used for intelligibility testing. The speech material in this case was taken from the sentences that are used by the Clarke School for the Deaf in its regular intelligibility testing program (Magner, 1972). The same groups also listened to the spontaneous speech in which the children described picture sequences. An intelligibility measure based on the number of "content" words heard correctly was determined for each listener group. Inasmuch as two of the experienced listeners had each tutored three of the children whose speech was being evaluated, the intelligibility data obtained from a tutor on the speech of a child that he had taught was not included in the analysis.

Table 4. List of attributes for which judgments were obtained from speech material consisting of words and phrases. The numbers at the right indicate correlation coefficients (Pearson r's) when scores from judgments of adequacy of velar control (in certain of the phrases and sentences) were compared with scores from all other types of judgments.

Overall adequacy of vowel articulation	0.30
Overall adequacy of consonant articulation	0.72
Overall adequacy of consonant blends	0.41
Consonant production:	
Initial consonants	0.75
Final consonants	0.65
Consonants in words	0.71
Consonants in sentences	0.71
Voiceless consonants	0.74
Voiced consonants	0.64
Plosive consonants	0.75
Fricative consonants	0.67
Vowel-like consonants	0.54
Nasal consonants	0.57
Judgments of voice quality:	
Harshness	0.22
Breathiness	-0.08
Composite quality	0.07
Pitch control:	
Mean pitch	0.54
pitch range	0.49
Intonation	0.33
Composite pitch	0.46
Temporal features and stress:	
Rate	0.37
Phrasing (pauses)	0.37
Stress	0.34
Composite	0.37
Velar Control	1.0

In addition to listener judgments, acoustic data were obtained from the recorded speech samples. These data included the measurements of nasality for words in isolation (which were included in the data for the larger sample of children as described above), together with measurements of nasality for the phrases listed in Table 3, following procedures to be described below.

Relation between Judged Adequacy of Velar Control and Other Listener-Evaluated Features

As part of the analysis of the listener-judgment data, two composite scores were obtained for each of the six students and each of the variables listed in Table 4, one for the speech sample recorded before training and one for that recorded after training. Each composite score was derived by pooling the judgments of the four listeners. Thus, for each of the attributes listed in Table 4, a set of twelve scores was derived. Correlation coefficients (Pearson r's) were obtained for all pairwise comparisons of these sets of scores.

The results of this analysis must be interpreted with caution because of the small samples involved; however, they are suggestive of directions future work might take. Hudgins (1949) has pointed out the desirability of taking advantage of correlations that may exist between different speech features because of the impracticality of measuring everything.

Inasmuch as nasality is often thought of as a "quality" deviation, or suprasegmental aspect of speech, that is relatively independent of problems associated with the articulation of individual speech sounds, the correlations between judgments of adequacy of velar control and the other variables listed in Table 4 are somewhat surprising. Nine of a total of 24 coefficients were significantly different from 0 ($p < .05$). All of these nine involved segmental features and in particular the articulation of consonants: consonant articulation in general ($r = .72$); articulation of consonants--in initial position of word ($r = .75$), in final position of word ($r = .65$), in isolated word context ($r = .71$), in sentence context ($r = .71$); articulation of voiceless consonants ($r = .74$), of voiced consonants ($r = .64$), of plosives ($r = .75$), and of fricatives ($r = .67$). The other two coefficients involving consonant articulation--vowel-like consonants ($r = .55$) and nasal consonants ($r = .57$)--were also relatively large, but not quite statistically significant. The correlations between the velar control judgment and suprasegmental features tended to be considerably smaller (.32 on the average). Perhaps most surprising of all is the fact that the correlation between the subjective assessment of velar control and overall voice quality was .07.

A possible explanation for the relatively high correlations between judged adequacy of velar control and articulation of obstruent consonants is that the production of obstruents requires pressure build-up in the mouth, and thus a raised velum (as discussed earlier). Inappropriate dynamic control of the velum for obstruent consonants could result in a lack of pressure increase, and hence an impression of poorly articulated consonants as well as of general nasal quality.

Judgments of velar control were also correlated with four measures of intelligibility representing the four possible combinations of naive and experienced listeners and read and spontaneous speech. In general, the coefficients were larger for experienced than for naive listeners (mean r's of .63 and .41), and for read than for spontaneous speech (mean r's of .61 and .43). However, only the coefficient representing the correlation between judged adequacy of velar control and the intelligibility of read speech as listened to by experienced listeners was statistically significant (r = .74).

Any inferences about the relationship between nasality--or any other property of the speech of the deaf--and intelligibility that are based on intelligibility data obtained in the laboratory must be made with care. The experience and expectations of a listener can have a large influence on his ability to understand the speech of a deaf person (Adams, 1914).

Objective Measurements of Nasality in Phrases and Sentences: Relation to Judgments of Adequacy of Velar Control

Measurements of the degree of nasality of isolated speech sounds, or of specific sounds within words spoken in isolation, represent one type of objective data that can be useful in evaluating speech. One would like in addition, however, some measure or measures that can be used to represent the adequacy, vis-a-vis nasality, of an entire meaningful utterance. As discussed above in connection with Figures 6 and 7 for normal-hearing speakers, the control of the velum within an utterance requires that the speaker lower the velum during consonantal closure interval for nasal consonants and raise the velum at all other times. A normal speaker also employs a certain amount of anticipatory and posticipatory coarticulation in velar control. Thus a vowel between two nasal consonants is usually produced with a lowered or partially lowered velum; when a nasal consonant is surrounded by sequences of nonnasal sonorants, the lowering of the velum anticipates the nasal consonant by 100 msec. or more, and there is a similar carryover of nasality following the nasal consonant; an obstruent consonant adjacent to a nasal requires rapid adjustment of the velum consonant with the requirements of the two segments.

These rules must presumably be learned by a deaf speaker if he is to produce fluent speech. Some of the problems experienced by the deaf children in exercising these kinds of velar control in a phrase or sentences are illustrated in Figure 11. The nasality display for a normal speaker producing the same phrase or sentence is shown for comparison in each case. In parts (a) and (b) of the figure (representing utterances from the same student), several problems are apparent: some vowels are nasalized when they should not be (you, your), and some nasal consonants are erroneously produced with the velum closed (drink, milk, money). The student who produced the display in part (c) apparently lowered the velum for all vowels, although she was able to raise the velum to produce obstruent consonants (e.g., the /d/ in Friday).

In an attempt to gain objective measures of the adequacy of velar control within such longer utterances, all of the phrases and sentences in Table 3 recorded by the six deaf children were examined and measured with the computer display. Three kinds of phrases and sentences are included within this speech sample: A: sentences with no nasals, B: sentences with many nasal consonants and no nonnasal obstruent consonant; and C: sentences with mixed nasal and nonnasal consonants. Two measures of adequacy of velar control have been determined from these sentences:

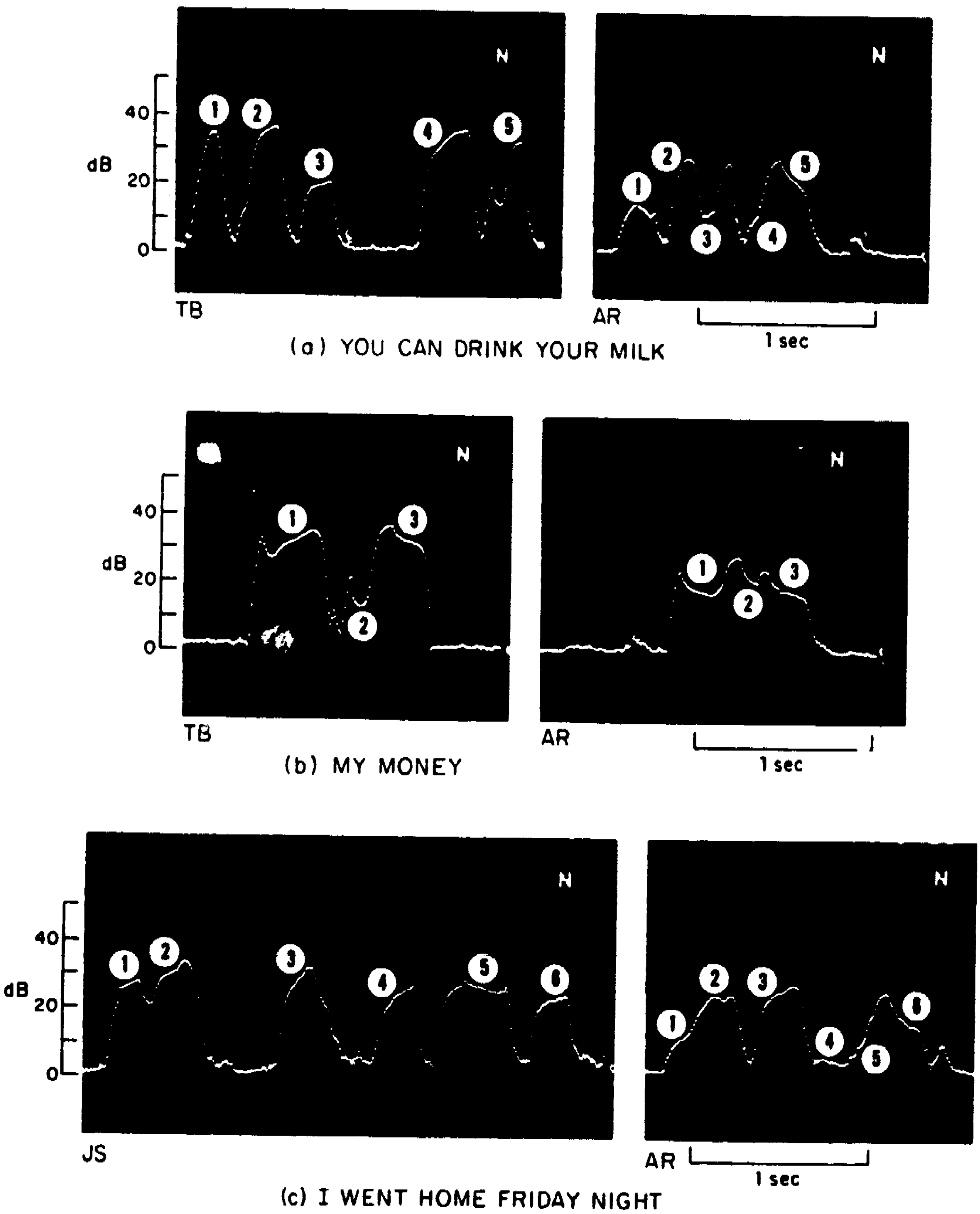

Fig. 11. Examples of output of nasal accelerometer vs. time for sentences produced by deaf students (left) and normal-hearing adult female (right). The positions of the vowel nuclei in the various syllables are identified by the numbers.

N_1 = (average nasality reading for nasal consonants in Type B sentences) - (average nasality reading for vowels in Type A sentences).

N_2 = (peak nasality reading for nasal consonants in Type C sentences) - (nasality reading for a nonnasal vowel in same sentence).

Both N_1 and N_2 are intended to indicate how well a speaker discriminates nasals from nonnasal vowels in sentence material: N_1 compares two types of sentences, and N_2 examines velar control within a sentence. Since the nasality readings are on a logarithmic scale, N_1 and N_2 are independent of the speech level. For normal speakers, N_1 and N_2 would be in the range 10-20 dB. (See Figure 2 for an example of a sentence where N_2 for a normal speaker is about 20 dB.) Values of N_1 and N_2 close to zero would suggest a failure to differentiate nasal and nonnasal sounds. These measures could even become negative for a severely hypernasal individual who also fails to nasalize some nasal consonants.

The measure does not avoid the problem mentioned in Footnote 1 above, namely that nasality can vary with voice effort; we are assuming that the voice effort would have been unlikely to vary much from utterance to utterance inasmuch as they were recorded at one sitting and within a short period of time. Another problem

is that sometimes considerable judgment must be exercised in deciding what to measure; if the articulation is very poor, syllables may be missing, spurious sounds may occur, or it may be difficult to determine from listening what constitutes a syllable. In the speech samples used there were relatively few cases of uncertainties of this sort that could not be resolved by listening several times to a difficult segment.

Measure N_1 was obtained for sentences 2 and 3 (all nasals) in Table 3, and sentence 1 (no nasals). Measure N_2 was obtained for sentences 4 (you), 5 (Fri), and 6 (dish), where the syllables in parentheses are the nonnasal syllables that were measured.

Two values of the indices N_1 and N_2 were computed in this way for each child, one based on the before-training and one on the after-training speech sample. These indices were then correlated with the velar control judgments made by listeners. The correlation (Pearson r) was 0.76 for N_1, 0.69 for N_2, and 0.78 for the mean $(N_1 + N_2)/2$. The scatter plot for the combined measure $(N_1 + N_2)/2$ is shown in Figure 12. The listener judgments are adjusted to lie on a scale from 0 (severe problem) to 5 (no problem). Given the size of the sample and the crudeness of the objective measure, we consider the result to be encouraging. One might hope, with some additional work, to define objective measures of the nasality of speech that would at least be a useful supplement to listener judgments, and might possibly obviate them.

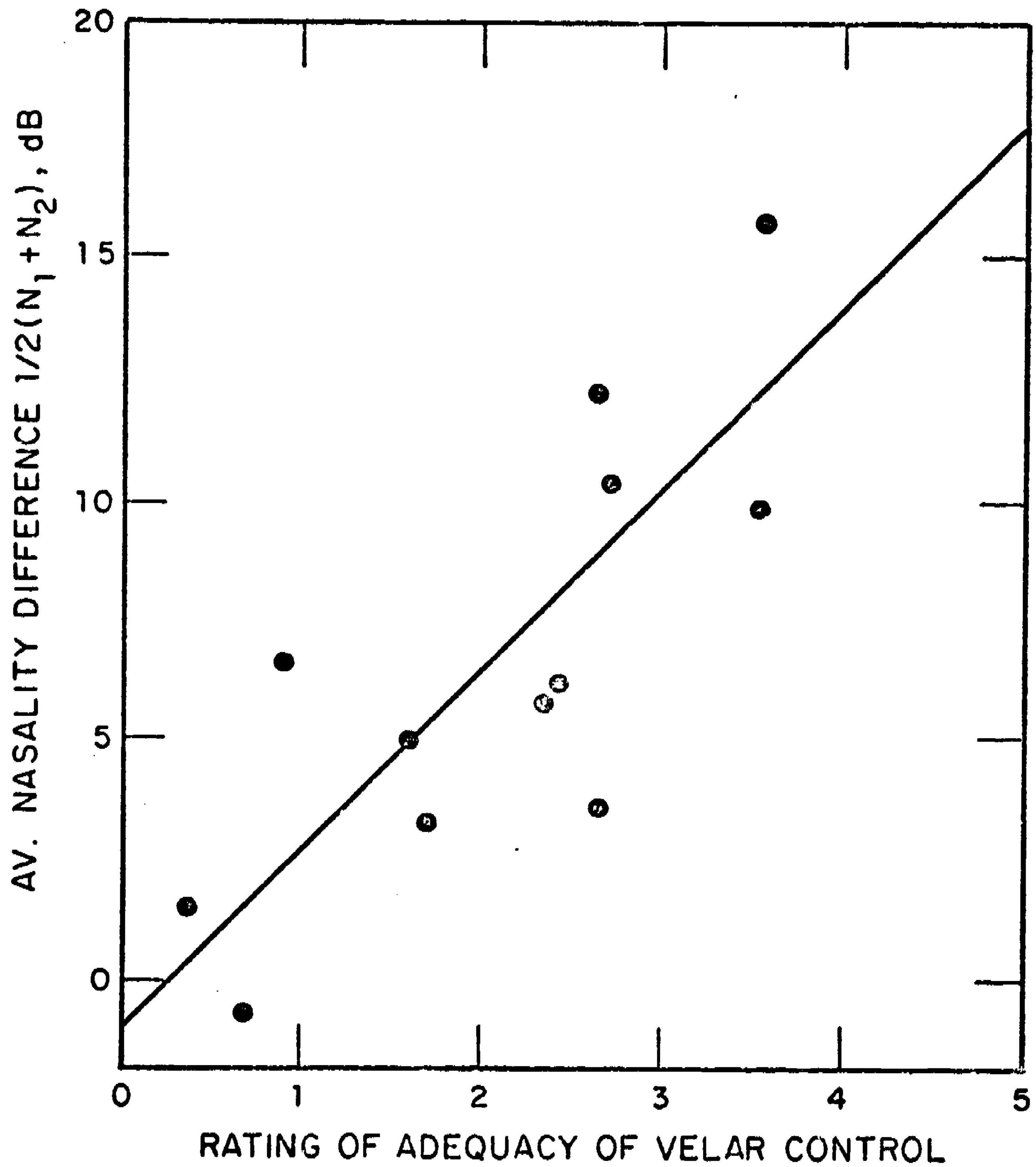

Fig. 12. The relation between nasality as indicated by objective measurements and adequacy of velar control as judged by listeners. The objective measure is difference between accelerometer output for nasals and for nonnasal vowels in sentences (see text). Data for six hearing-impaired students, each recorded on two occasions. The line is fitted by eye.

USE OF NASALITY DISPLAY FOR TRAINING OF VELAR CONTROL

A display of nasality versus time has been used as an aid for training of velar control for several deaf students. The details of the display and the general manner in which it is used by the teacher and student are described elsewhere (Nickerson and Stevens, 1973; Nickerson, et al., 1974). The following features of the system should be noted, however; (1) To assist in the training of velar control, the nasality display (of the type shown in Figure 2) is combined with an indication of voicing, so that wheneve' the utterance is voiced, a horizontal line appears at the base of the nasality display. (2) A criterion line can be displayed along with the nasality curve, to indicate to the student a particular nasality value that he should attempt to keep below (for a nonnasal utterance) or above (for a nasal consonant). The position of this line can be adjusted by the teacher (or student). (3) A reference display can be generated by the teacher, and this display remains stationary on the upper half of the screen when the student attempts an utterance. (4) The displayed curve moves from right to left in real time, the current instant of time being represented by a fixed location at the right of the screen. (5) The past two seconds of the display can be frozen on the screen by depressing a button, and this stored display can be replayed, together with the audio speech signal. (6) Presentation of the display can be simultaneous with the utterance, or can be delayed until the teacher (or student) wishes to see it. The delay feature

allows the student to assess the adequacy of his utterance, based on proprioceptive cues, before verifying this judgment with the visual display.

Various approaches to the training of velar control are being attempted, depending on the nature of the student's speech problem, his age, and his response to the training. Among the vocalizations or other utterances that are being used as training materials are the following: (1) A long steady vowel with nasality reading below a specified criterion, as determined from Figure 4. (2) Simple monosyllabic consonant-vowel (CV) or CVC utterances with nasality readings within specified criteria. The utterances include nonnasal words, words in which both consonants are nasals, and words with one nasal consonant and one obstruent consonant. (3) Words containing nasal-obstruent clusters, such as jump, cinder, and think. (4) Phrases or sentences containing no nasal consonants. (5) Phrases or sentences in which both nasals and other consonant types are included.

For most students, the training is carried out on a tutorial basis in a series of sessions with a teacher present. After an initial period of orientation and training, some students are able to work on a self-tutoring basis without the teacher present. Data are being collected to assess the progress of students who are being trained by these procedures. The results of that evaluation and a more detailed discussion of the training procedures will be presented in a future report.

NOTES

1. One of the problems associated with developing measures, either of overall nasality or of changes in velar opening as a function of time, is the fact that the nasality function is not independent of the intensity of the speech. One way to accommodate this fact would be to develop a measure that relates the amount of energy that is detected by the nose accelerometer with the amount that is picked up by the voice microphone. This is not an entirely straightforward comparison, however, inasmuch as the speech amplitude varies considerably with different speech sounds, and in particular tends often to decrease during the production of a properly nasalized sound. The problem is not serious as long as the speaker maintains a reasonably constant voice effort. Variations in level due to changes in voice effort (including changes in stress) are not likely to be more than about $\pm$ 2 dB under normal circumstances, whereas changes in the output of the nasal accelerometer due to velar opening and closing are in the range 10-20 dB.

2. This list is part of a longer list of words containing a variety of vowels, consonants, and consonant clusters. The items in Table 1 represent only the nondiphthongized nonnasal vowels and the nasal consonants and consonant clusters.

3. Another possibility is that normal speakers actually produce high vowels with a lower velum and hence with greater acoustic coupling to the nasal cavity through the partially open velopharyngeal port. They may use this strategy either because the perceptual effect of increased nasal coupling is less for high vowels than for nonhigh vowels or because of interaction between muscle groups controlling velar opening and those controlling tongue position. Perceptual studies suggest, however, that the explanation in terms of the influence of nasal coupling on perception of nasality is not valid (House and Stevens, 1956), since a given degree of opening of the velopharyngeal port appears to make high vowels sound more nasal than low vowels.

4. The procedure for detecting "amplitude" involves summing the rectified and smoothed outputs of a series of band-pass filters (with center frequencies ranging from 260 to 3300 Hz), and log-converting the result (see Nickerson, et al., 1974).

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REFERENCES

Adams, M. E. The intelligibility of the speech of the deaf. *American Annals of the Deaf*, 1914, *59*, 451-460.

Brehm, F. E. Speech correction. *American Annals of the Deaf*, 1922, *67*, 361-370.

Bradford, L. J., Brooks, A. R., and Shelton, R. L. Clinical judgments of hypernasality in cleft palate children. *Cleft Palate Journal*, 1964, *1*, 329-335.

Colton, R. H. and Cooker, H. S. Perceived nasality in the speech of the deaf. *Journal of Speech and Hearing Research*, 1968, *11*, 553-559.

Delattre, P. C. Two acoustic correlates of nasality studied by synthesis. Paper read before the Modern Language Association, Chicago, Illinois, December 27, 1955.

Fletcher, S. G. Theory and instrumentation for quantitative measurement of nasality. *Cleft Palate Journal*, 1970, *7*, 601-609.

Fujimura, O. Spectra of nasalized vowels. Quarterly Progress Report, Research Laboratory of Electronics, Massachusetts Institute of Technology, July 15, 1960, 214-218.

Holbrook, A. and Crawford, G. H. Modification of speech behavior of the deaf (hypernasality). Paper presented to Conference of Executives of American Schools for the Deaf, St. Augustine, Florida, April, 1970.

House, A. S. and Stevens, K. N. Analog studies of the nasalization of vowels. Journal of Speech and Hearing Disorders, 1956, 21, 218-232.

Hudgins, C. V. A comparative study of the speech coordination of deaf and normal subjects. Journal of Genetic Psychology, 1934, LXIV, 3.

Hudgins, C. V. A method of appraising the speech of the deaf. The Volta Review, 1949, 51 (12), 597-601, 638.

Lubker, J. F. and Moll, K. L. Simultaneous oral-nasal air flow measurements and cinefluorographic observations during speech production. Cleft Palate Journal, 1965, 2, 257-272.

Magner, N. A speech intelligibility test for deaf children. Clarke School for the Deaf, Northampton, Mass., 1972.

Nickerson, R. S. and Stevens, K. N. Teaching speech to the deaf: Can a computer help? IEEE Transactions on Audio and Electroacoustics, 1973, AU-21, 445-455.

Nickerson, R. S., Kalikow, D. N., and Stevens, K. N. A computer-based system of speech-training aids for the deaf: A progress report. BBN Report No. 2901, Sept. 1974 to U.S. Office of Education under Contract No. OEC-0-71-4670(615).

Quigley, L. F., Shiere, F. R., Webster, R. C., and Cobb, C. M. Measuring palatopharyngeal competence with the nasal anemometer. Cleft Palate Journal, 1964, 1, 304-313.

Shelton, R. L., Knox, A. W., Arndt, W. B., and Elbert, M. The relationship between nasality score values and oral and nasal sound pressure level. Journal of Speech and Hearing Research, 1967, 10. 542-548.

Stevens, K. N., Kalikow, D. N., and Willemain, T. R. The use of a miniature accelerometer for detecting glottal waveforms and nasality. BBN Report No. 2907, Sept. 1974 to U.S. Office of Education under Contract No. OEC-0-71-4670(615).